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Fusion of imaging spectrometer and LIDAR data over combined radiative transfer models for forest canopy characterization

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Abstract

A comprehensive canopy characterization of forests is derived from the combined remote sensing signal of imaging spectrometry and large footprint LIDAR. The inversion of two linked physically based Radiative Transfer Models (RTM) provided the platform for synergistically exploiting the specific and independent information dimensions obtained by the two earth observation systems. Due to its measurement principle, LIght Detection And Ranging (LIDAR) is particularly suited to assess the horizontal and vertical canopy structure of forests, while the spectral measurements of imaging spectrometry are specifically rich on information for biophysical and -chemical canopy properties. In the presented approach, the specific information content inherent to the observations of the respective sensor was not only able to complement the canopy characterization, but also helped to solve the ill-posed problem of the RTM inversion. The theoretical feasibility of the proposed earth observation concept has been tested on a synthetic data set generated by a forest growth model for a wide range of forest stands. Robust estimates on forest canopy characteristics were achieved, ranging from maximal tree height, fractional cover (fcover), Leaf Area Index (LAI) to the foliage chlorophyll and water content. The introduction of prior information on the canopy structure derived from large footprint LIDAR observations significantly improved the retrieval performance relative to estimates based solely on spectral information.

Keywords: Imaging Spectrometer; LIDAR; Radiative Transfer Model; LAI; Fractional cover; Tree height; Canopy structure; Biomass; Forest; Inversion; Fusion; Forest growth model

1. Introduction

Vegetation controls a large part of the heat and mass fluxes within the terrestrial biosphere. The major physiological processes, such as evapotranspiration and photosynthesis, responsible within vegetation for energy and mass exchanges are driven by the canopy structure as well as the biochemistry of the foliage. For the understanding and monitoring of the typically heterogeneous and dynamic terrestrial biosphere a comprehensive and robust characterization of vegetation canopies is thus required (Sellers et al., 1997).

The vegetated land surface is often characterized by passive optical remote sensing sensors observing the spectral properties of the surface. The spectral information content is able to provide estimates on biophysical parameters, such as Leaf Area Index (LAI) and fractional cover, as well as on parameters related to the foliage biochemistry, such as the Fraction of Absorbed Photosynthetic Active Radiation (FAPAR), up to global scale (Myneni et al., 2002; Widlowski et al., 2001). Recently, the active optical system LIDAR started to provide information on the vertical distribution of canopy elements within a vegetation canopy (Drake et al., 2002b; Lefsky et al., 2002). While large footprint LIDAR capture the full vertical waveform over a canopy potentially form a spaceborne platform, airborne small footprint LIDAR can resolve the canopy structure up to a single tree (Harding et al., 2001; Hyyppa et al., 2001; Morsdorf et al., 2006, 2004; Naesset & Okland, 2002). The direct LIDAR observations of vertical canopy structure can thus present an independent information source complementing the spectral information content for a comprehensive canopy characterization (Gillespie et al., 2004; Hill & Thomson, 2005).

The complexity of a vegetation canopy and uncertainties related to measurements and retrieval algorithm cause the vegetation characterization by remote sensing to be an ill-posed problem (Combal et al., 2003). The radiative transfer within a canopy depends on the complex 3-D canopy structure defined by the geometry, position and density of canopy elements as well as the optical properties of each canopy element (Goel & Thompson, 2000). Physically based Radiative Transfer Models (RTM) have been developed to describe the interaction of radiation with the diverse canopy components at foliage and canopy level (Govaerts, 1996; Jacquemoud & Baret, 1990;

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Kuusk & Nilson, 2000; Ni-Meister et al., 2001; Sun & Ranson, 2000). RTM provide thus an explicit connection between canopy variables, observation and illumination geometry and the resulting remote sensing signature. Nevertheless, assumptions and number of parameters of most invertible RTM rend them to an intrinsic underdetermined system. This fact and measurement uncertainties lead to multiple possible solutions when RTM are inverted against remote sensing observations. For an improved retrieval of vegetation characteristics by RTM inversion, the number of independent information sources should thus be increased (Verstraete et al., 1996).

For the characterization of heterogeneous forest canopies we propose to exploit the independent information dimensions provided by the two earth observation systems imaging spectrometry and LIDAR. While the spectral measurements of imaging spectrometry bear information on the foliar biochemical composition and only an indirect link to the canopy structure, LIDAR observations provide direct measurements of the vertical and horizontal canopy structure. The LIDAR signal, e.g. recorded as full waveform, can thus improve the accuracy and robustness of RTM inversion based solely on spectral information by reducing the uncertainties related to canopy structure. On the other hand, accurate interpretation of the LIDAR signal depends on the spectral properties of canopy elements and background. The two sensors and their information dimension are thus mutually dependent but can also complement each other.

Radiative transfer modeling of the remote sensing signals as observed by imaging spectrometry and LIDAR is described by the same basic physical processes. Consequently, an interface between two RTM based on the same physical concept and sharing common input parameters can be established. A common forest stand parameterization is used by the two models to generate a combined spectral and LIDAR waveform signature of the respective canopy. RTM inversion based on a Look Up Table (LUT) comprising the combined remote sensing signatures of imaging spectrometry and LIDAR as a function of a common forest stand parameterization offers thus a simple approach to exploit synergistically these independent information dimensions. In the presented study prior information on the canopy structure derived from the LIDAR information helps to improve the retrieval performance. Similar approaches have been promoted using prior information derived from the spatial, temporal and directional information dimension of earth observation (Atzberger, 2004; Knyazikhin et al., 1998; Koetz et al., 2005; Widlowski et al., 2004).

The objective of the presented research is to show the theoretical feasibility of an observation concept that fully exploits the information dimensions provided by the two earth observation systems imaging spectrometry and large footprint LIDAR to characterize a forest canopy. The exploitation of the two independent information sources ensures a robust parameter retrieval but also provides an enhanced canopy characterization, including the foliage biochemical content as well as the horizontal and vertical canopy structure. The methodology has been developed and evaluated on a synthetic data set, which allowed for a comprehensive validation over forest stands of changing age and under different environmental conditions generated by a forest growth model. The proposed approach finally also bears implications and shows potential for future multi-sensor earth observation platforms such as the proposed spaceborne mission Carbon-3D (Hese et al., 2005).

6. Conclusions

Remote sensing of vegetation properties has been shown to be a generally ill-posed problem, partly due to the available indirect detection methods and measurement uncertainties but also due to the limited representation of the involved processes in the retrieval. This includes the inversion of RTM, because even physically based radiative transfer models have to be partly based on assumptions and parameterizations in order to be invertible. Consequently the introduction of prior or ancillary information into the retrieval process is a necessary and useful approach to increase the robustness of canopy parameter estimation by remote sensing. One promising way of deriving prior information is to exploit independent information dimensions provided by multiple sensors.

The presented study showed the feasibility and potential for the combined information exploitation of multiple sensors based on physically based radiative transfer modeling. The two information dimensions provided by imaging spectrometry and LIDAR were successfully used to derive a comprehensive canopy characterization, relevant for the assessment of biomass, productivity of vegetation and risk of natural hazards such as forest fires (Chuvieco, 2003; Sellers et al., 1997). The specific information content, inherent to the observations of the respective sensors, was able to complement the canopy characterization but also helped to stabilize the RTM inversion. Prior information derived from LIDAR observations helped to improve the retrieval performance of the canopy structure, which is in general only indirectly and thus with relative high uncertainties inferable from pure spectral information. The results of the study provided robust estimates of the vertical and horizontal canopy structure as well as biophysical and -chemical canopy parameters for a wide range of forest stands. The major limitation of the results was its validation relative to a synthetic data set based on simulations. Before an operational use of this observation concept it needs to be tested on actual measurements of the respective sensors and validated against a large variability of real field measurements. However, the generation of the data set by an ecologically sound forest growth model linked to physically based RTM ensured the reproduction of many processes important in reality. The advantage of a synthetic data set on the other hand is the wide range of forest stands conditions covered and avoiding limitations related to measurement errors. The explicit description of the canopy structure by the forest growth model also allowed for an increased understanding of the processes impacting the LIDAR waveform signal and thus led to an improved retrieval algorithm.

Although these findings are based on a synthetic data set and real measurements have to confirm them, they present a possible observation concept for future space-borne Earth-Observation platforms with multiple sensors. For example the proposed mission Carbon-3D, which is supposed to provide global biomass estimates, is based on similar observation techniques including an multi-spectral/-angular sensor and a large footprint LIDAR (Hese et al., 2005). The presented exploitation of multiple sensors could also be principally applied to existing space-borne instruments on separate platforms such as the imaging spectrometers Hyperion (Ungar et al., 2003) and CHRIS (Barnsley et al., 2004) as well as the large footprint LIDAR GLAS (Lefsky et al., 2005). However, the spatial resolution of GLAS is not adapted to the needs of vegetation studies and the revisiting frequency of the imaging spectrometers has to be increased for most applications.